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MYOELECTRIC CONTROL IN A PRECISION TRACKING TASK

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THESIS

Myoelectric Control in a Precision
Tracking Task

by

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March 1973

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ABSTRACT

Basic research was conducted into the ability of a person to perform a precision tracking task using the myoelectric output of the forearm. The tracking task was performed using both a conventional force stick and the electric output from the same muscle groups involved in operating the force stick. Multiple trials with both systems enabled a good comparison to be made between both control modes. The feasibility of myoelectric control using easily applied surface electrodes was demonstrated as was the existance of a significant learning curve associated with the myoelectric control system. Relative effectiveness of the myoelectric control system ranged from 25 percent to 55 percent of that of the force stick and was highly time correlated. Further learning beyond the duration of this experiment was also implied.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

A. BACKGROUND

The Eighteenth century discovery by Galvani of the existance of a relationship between muscular contraction and an accompanying electrical signal was the beginning of the study of the myoelectric signal, known also as an EMG or electromyographic signal. This phenomenon has been the object of extensive study in more recent years, following the development of equipment sufficiently sensitive to identify and analyze a signal of this magnitude. Virtually all of this research has been directed toward clinical applications of these signals. The three primary areas of application include neuromuscular abnormality diagnosis (Norris 1963; Chaffin 1969), establishment of the relationship between electrical output and such parameters as force, velocity, and power (Wilkie 1950; Bigland and Lippold 1954; Neil 1971), and the use of the myoelectric signal as a control signal for powered prosthetic devices. (Battye et al. 1955)

Relatively little has been accomplished in the investigation of the use of myoelectric signals as independent control signals in the biologically unfaulted organism. Specifically, the factors concerning the potential use of this signal in an environment prohibiting conventional machine interface and the possible advantages which a myoelectric control system might possess over a more conventional control system have not been well explored. The need therefore exists for the conduct of basic research into the capabilities and characteristics of myoelectric control systems.

B. MYOELECTRICITY

The method of operation of the neuromuscular system in man is one which has been well known for many years. Basically, it is a machine which, on demand, is capable of converting stored bodily energy into electrochemical attraction, which, in turn, produces a shortening of the length of a muscle cell. A typical skeletal or voluntary muscle is composed of numerous motor-units. The motor-unit, which can be regarded as the basic unit of contraction in muscle, consists of many muscle fibers, all commonly innervated. Each muscle fiber is, in turn, composed of thousands of myofibrils. Each myofibril can be seen to be a longitudinal aggregation of muscle cells or sarcomeres.

A section of myofibril showing the arrangement within one sarcomere is illustrated in Fig. 1. An electrochemical bond exists between the actin and myosin filaments, the changes in which result in the contraction or relaxation of each muscle cell.

Control of the voluntary muscles is exercised by the higher centers of the brain, the spinal cord, and by a rather complex positional feedback system. When a contraction of a muscle is ordered by one of these systems, an electrical impulse is sent via the nervous system to some, or all, of the motor units of that muscle. At the end plate, or juncture of the nerve with the muscle fiber, the electrical signal causes release of the chemical acetylcholine into close proximity with the outer membrane of the muscle fiber. The acetylcholine, in turn causes the permeability of the membrane to change and allows the flow of calcium ions to the interior of the cell. The increase in calcium in the interior of the cell causes heightened electrochemical bonding between the actin and myosin filaments, resulting in shortening of the length of the cell.

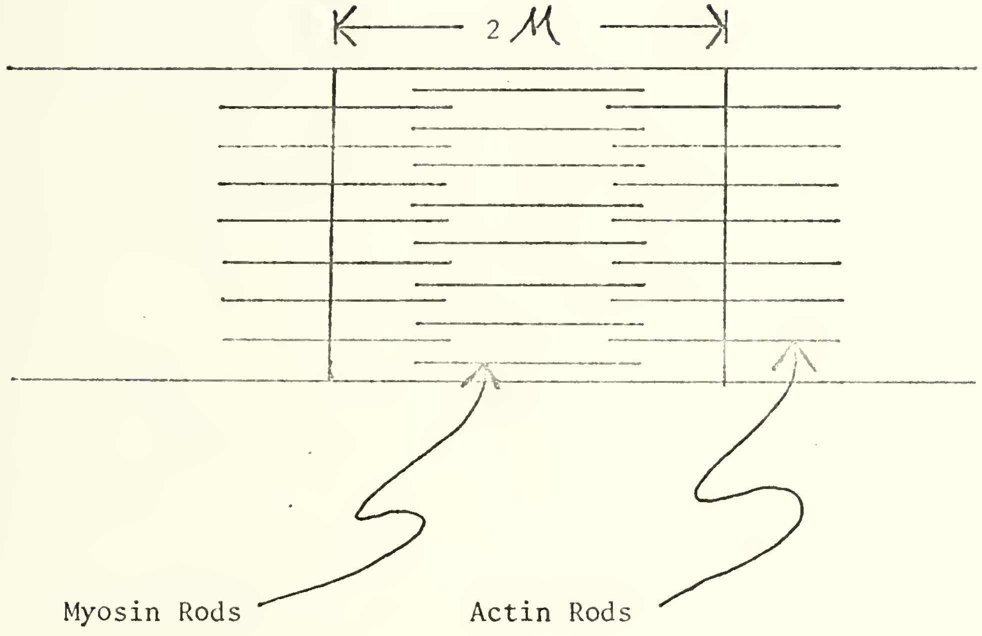

Figure 1. Myofibril Section Showing One Sarcomere

The difference in the membrane potential at the point of innervation causes adjacent membrane to increase its permeability to calcium and the net result is the initiation of a wave of depolarization which sweeps the entire length of the muscle fiber, causing contraction of all involved muscle cells. It is this wave of depolarization, coming from hundreds of motor units, which is detectable by surface electrodes and is known as the myoelectric signal.

II. EXPERIMENTAL PROCEDURE

A. GOAL OF THE EXPERIMENT

The experiment was designed to provide a comparison between a person's ability to perform a task utilizing a conventional means of control, and his performance with the control signal being generated electrically by the same muscles as with the conventional control. The task chosen to be performed was a one-dimensional compensatory tracking task. The subjects would be required to track in opposition to an input signal using a "side-arm" mounted, force-sensitive, rigid control stick. For one-half of the trials the control signals were generated by the stick, but for the other half of the trials the control signals would be taken from surface electrodes. Those were situated on the forearm above the muscles normally used by the subjects to exert the required force on the control stick. In this way, the subjects would be performing the task in, as nearly as possible, an identical manner, regardless of which system was in use. This would allow the autonomic nervous system to control most of the subjects' response, and not require that the myoelectric control be a function of the higher thought processes. This in turn would eliminate any additional time lag and its associated loss of accuracy of various subjects' tracking with both control systems, a basis for comparison of the two systems would be obtained.

B. SUBJECT PREPARATION

The subjects utilized in the experiment were eight U. S. Naval officers, all students at the Naval Postgraduate School, and were

uncompensated for their participation. Four of the eight were qualified Naval Aviators while the other four had little or no aviation experience. Although the force-stick employed in this experiment was equipped with a hand grip employed in some military aircraft, the positioning of the stick and the nature of the task made the experiment different enough from the learned skills of piloting that it was felt there would be no advantage given to either group.

Prior to experimentation, the entire purpose and conduct of the experiment was explained to the subjects. They did not, however, receive any information during the experiment to indicate their performance relative to prior subjects.

Prior to attachment of the skin electrodes, the affected skin areas of the forearm were washed with abrasive soap, dried, and wiped with alcohol.

During the experimentation, which lasted approximately two and one-half hours, efforts were made to keep the subjects comfortable and refreshed so as to reduce the effects of fatigue as much as possible.

C. EQUIPMENT AND SET-UP

The electrodes used were Beckman type 650418 Skin Electrodes. A total of five electrodes were applied to each subject, two for each involved muscle group and a common ground. In order to achieve some consistancy of placement between subjects, a technique employed previously by Neil (1971) was used. The electrode pairs which would be uitlized on the muscle sites were mounted to a one inch by three inch strip of one-fourth inch thick Plexiglas, the electrode centers being two inches apart. These electrodes were held in place by a two-inch wide elastic and Velcro band, while the ground electrode was attached

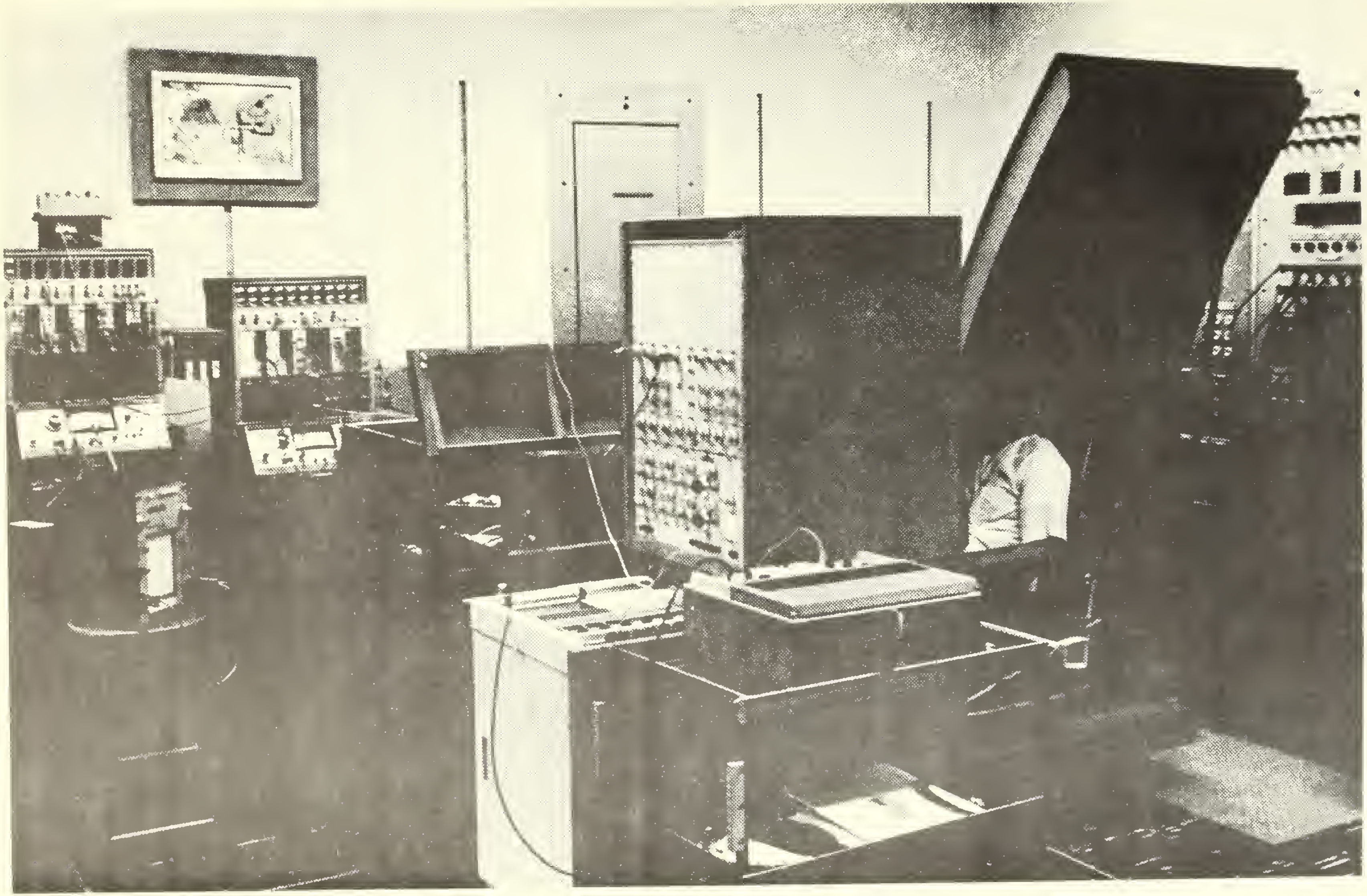

Figure 2. Experimental Apparatus

by a conventional adhesive collar. Beckman Electrode Paste was used at the skin-electrode interface to minimize resistance.

One electrode pair was situated over the Flexor Carpi Radialis with the uppermost electrode two and one-half inches from the Medial Epicondyle. The other electrode pair was located above the Extensor Carpi Ulnaris, the upper electrode situated two and one-half inches from the plane of flexion of the elbow.

A Beckman type RM Physiological Recorder with 9852 EMG Integrator Couplers installed was used to initially integrate and amplify the myoelectric signals and to reject any changes to the integrated signal occuring at a rate greater than 30 Hz.

During the experiment, the subjects were seated in a basic cockpit mock-up. The force stick was positioned as a "side arm" controller, adjacent to the subject's right side, at a vertical height and forward distance appropriate to a seated, right arm flexed posture. The task was displayed on an oscilloscope mounted approximately three feet in front of the subject. The tasking signal was previously recorded on magnetic tape and was pseudo-random, being the sum of five different sine waves. Depending upon the control system being employed, either the amplified voltage output of the force stick, or the amplified resultant output of the forearm muscles was algebraically summed with the tasking signal in a desk-top analog computer. This summed signal was then sent to the oscilloscope where it determined the horizontal position of a dot of light. The tasking signal alone had the capability of displacing the dot a maximum of approximately 5 cm. to either side of the center and would drive the dot at a maximum rate of about 2 cm/sec.

Figure 3. Subject Positioned for Experimentation

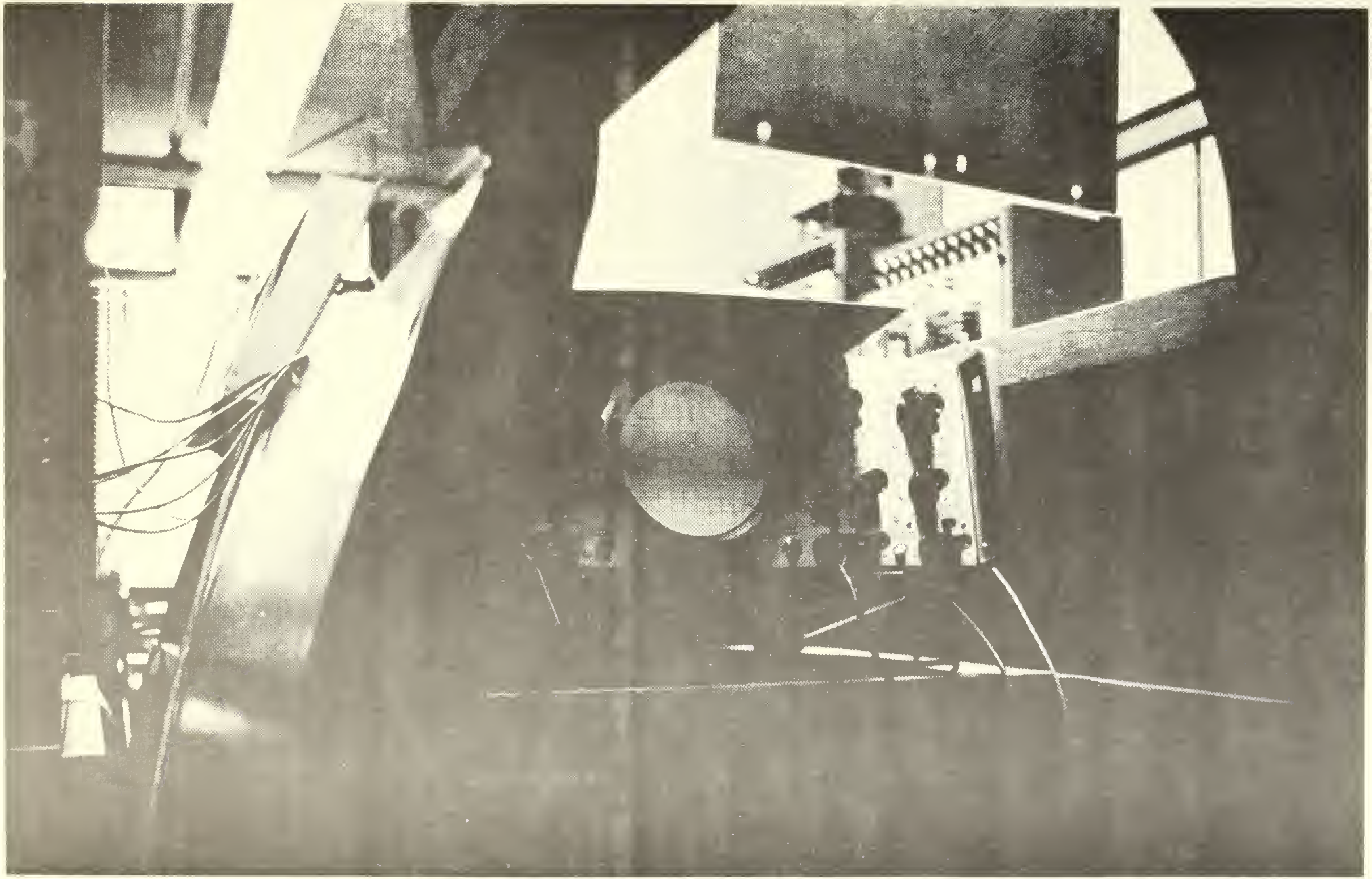

Figure 4. Tracking Display

D. CONDUCT OF EXPERIMENT

After preparation and hook-up to the apparatus, the subjects were allowed to familiarize themselves with the use of both control systems. They were first allowed to observe the reaction of the light dot to the force stick in the absence of the tasking signal and then with the tasking signal energized. This same procedure was repeated with the myoelectric control system activated and the amplification of this system was adjusted to provide the subjects with the same subjective "feel" or sensitivity as they had experienced with the force stick. This was necessary in order to eliminate the inter-subject difference in myoelectric output from the forearm. This procedure typically lasted from 6 to 10 minutes.

Following familiarization, data collection commenced. Each segment of the experiment consisted of ten trials, each trial lasting 30 seconds, with 30 seconds between trials. Within a segment, all ten trials were performed with the same control system, the force stick being utilized in the first segment, followed by the myoelectric system in the second, and so forth. This was repeated for ten segments, until 50 trials had been completed with each control system. Each segment lasted nine and one-half minutes and the subjects were allowed to rest between each segment as the control systems were being changed. These rest periods lasted between one and five minutes, the duration being up to the individual subject's feeling of fatigue and desire for rest. The total time involved in the data collection portion of the experiment was approximately two hours, with the subjects actually performing the task for 50 minutes.

III. DATA COLLECTION AND ANALYSIS

The measure of effectiveness chosen to provide a comparison between the tracking abilities of the two involved systems was the absolute value of the total error throughout each 30-second trial. In order to collect this data, the resultant voltage signal to the oscilloscope, composed of the sum of the tasking signal and the tracking signal, was recorded on a Hewlett-Packard 3960 Series Instrumentation Tape Recorder. A manual keying signal was also recorded at the commencement of each 30-second tracking task. Upon completion of experimentation, the tape was replayed into a PDP-8 digital computer where the sampling took place. Upon receipt of the keying signal, the computer was programmed to commence sampling the voltage at the rate of one sample every 0.0004 second and to make 7,500 samples. Since the voltages involved were in the range $\pm$ 1.0, the program computed the sum of the absolute value of each of the voltages. Thus, the effectiveness measure for each 30-second trial was

$$E_j = \sum_{i=i}^{7500} |V_i|$$

where V_i = instantaneous voltage reading and E_j = total error score for trial j. This score is the Total Absolute Error for a trial and was used in place of Average Absolute Error (Kelly 1969) due to the magnitude of the numbers involved. Division by 7,500 would have produced scores in the small decimal range, producing errors of significance when statistical calculations were performed.

A total of eight subjects completed the experiment, yielding 400 measures of tracking proficiency for each of the control systems.

To determine the difficulty of the task, analysis was performed to discover the existance of any learning effect during the testing session. After averaging the error scores across all eight subjects, a test of runs above and below the median was conducted. No significant increase in performance was noted ($u = 28, \mu_u = 26, \sigma_u = 3.5$) when the force stick was used. The same test applied to the trials using the myoelectric control system yielded ($u = 10, \mu_u = 26, \sigma_u = 3.5$) which showed a significant increase in performance ($p < .025$).

For each system, the first 10 trials were compared to the last 10 trials for all subjects. The Wilcoxon Sign Test for Differences Between Related Samples was applied to the data with the result that there was no significant change in the performance with the force stick ($n' = 8$, min. rank sum = 10). However, performance with the myoelectric control system improved a significant amount ($n' = 8$, min. rank sum = 0) ($p < .01$).

For a parametric test, the t-test for related measures was applied to the same data as in the Wilcoxon test. The results for the force stick ($t = 1.12$) showed no significant learning while the accuracy measures for the myoelectric control system were shown to exhibit a significant increase in performance ($t = 3.277$, $p < .01$).

Further analysis of the change in performance over time was accomplished by conducting a polynomial regression on each set of tracking performance data using time (i.e. index numbers 1-50) as the independant variable (Fig. 5). The primary component of the regression on the scores for both systems was linear, with a moderately significant

Table I. Total Absolute Error

TRIAL	FORCE STICK	MYOELECTRIC SYSTEM
1	60.78	199.45
2	58.01	168.26
3	54.96	165.67
4	59.33	183.30
5	55.43	163.33
6	51.69	182.66
7	56.65	207.64
8	57.50	188.15
9	48.91	197.27
10	58.31	194.19
11	53.04	177.31
12	51.13	201.89
13	54.19	201.73
14	53.34	154.88
15	52.86	186.52
16	56.16	213.05
17	50.94	160.40
18	53.82	169.85
19	48.55	173.32
20	55.93	156.26
21	56.30	152.44
22	53.03	104.37
23	52.75	111.75
24	51.26	117.63
25	49.58	130.99
26	47.69	115.03
27	50.38	127.72
28	53.75	135.09
29	54.00	130.91
30	50.41	133.36
31	52.77	106.54
32	57.66	112.88
33	52.21	139.07
34	54.74	95.76
35	51.59	115.81
36	56.20	111.06
37	49.94	116.31
38	52.09	105.90
39	51.36	116.58
40	51.67	119.34
41	55.97	105.14
42	55.47	112.37
43	45.10	96.08
44	52.12	105.01
45	54.49	103.12
46	48.78	113.91
47	55.67	112.06
48	46.18	110 90
49	49.87	106.73
50	50.35	111.42

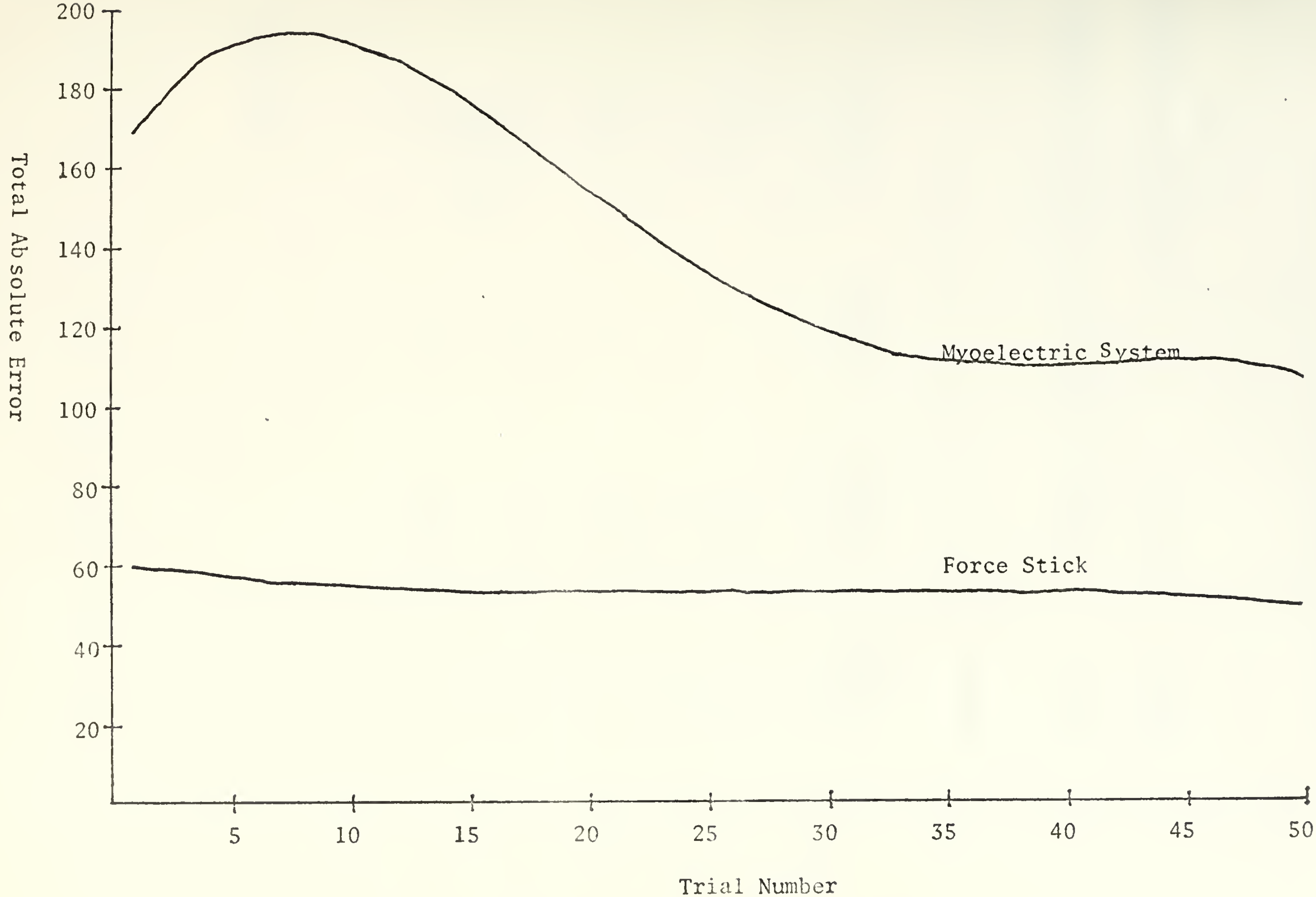

Figure 5. Polynomial Regression on Total Absolute Error

Table II. Polynomial Regression on Averages of Force-Stick Performance

Intercept 59.79351

Regression Coefficients

-0.87386	0.03311	-0.00039	-0.00000

Standard Error of Regression Coefficients

0.62166	0.04888	0.0143	0.00001

Analysis of Variance for 4th Degree Polynomial

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F
Linear term	1	112.872	112.872	13.26*
Quadratic term	1	13.999	13.999	1.64
Cubic Term	1	43.695	43.695	5.13**
Quartic term	1	0.00	0.00	0.00
Deviation about regression	45	383.048	8.51	
Total	49	553.614		

* $p < .001$
** $p < .05$

Table III. Polynomial Regression on Averages of Myoelectric System Performance

Intercept 159.25858

Regression Coefficients

10.15927	-0.91500	0.02349	-0.00019

Standard Error of Regression Coefficients

3.34357	0.26290	0.00771	0.00008

Analysis of Variance for 4th Degree Polynomial

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F
Linear term	1	46273.316	46273.316	187.92*
Quadratic term	1	986.859	986.859	4.01
Cubic term	1	3918.738	3918.738	15.91*
Quartic term	1	1637.191	1637.191	6.65**
Deviation about regression	45	11080.809	246.240	
Total	49	63896.913		

* $p < .001$
** $p < .05$

cubic term for the force stick. On the other hand, the myoelectric control system data displayed a highly significant cubic term and a moderately significant quartic term.

Analysis was next performed on the 50 Total Absolute Error (TAE) scores for each control system obtained by averaging across all eight subjects. The existance of a relationship between these sets of data was confirmed by the correlation coefficient ($\rho = 0.38$). Hypothesis testing on the correlation coefficient ($H_o : \rho = 0.0$) for n = 50 shows significance at the $p < .05$ level for a two-tailed test. A linear regression of TAE with the force stick produced a predictive equation of $Y = -74.9 + 4.093X$ with an F-ratio of 8.1 ($p < .01$).

A relative effectiveness measure to quantify tracking performance was generated by computing the ratio of the overall average of Total Absolute Error with the force stick (53.094) to the Total Absolute Error with the myoelectric control system averaged across subjects. The resultant numbers show the percentage effectiveness of the myoelectric system with the force stick as a reference (Table IV). The increase in effectiveness indicated was shown to be highly correlated with time ($\rho = 0.86$; $p < .01$). Linear regression of effectiveness on time on task resulted in the equation $Y = 0.255 + 0.006X$ with an F-ratio of 137.4.

Comparison of performance between the two systems on a scale more closely associated with the scales used for measurement was accomplished through use of the arithmetic difference between the Total Absolute Error averages for each of the 50 trials. A strong correlation with time was likewise found with this measure ($\rho = 0.84$), with a linear regression producing a fit to the line $Y = 140.417 - 2.004X$.

Table IV. Relative Effectiveness of Myoelectric Control System

Trial	% Effectiveness
1	0.2662
2	0.3155
3	0.3205
4	0.2897
5	0.3251
6	0.2907
7	0.2557
8	0.2822
9	0.2691
10	0.2734
11	0.2994
12	0.2630
13	0.2632
14	0.3428
15	0.2847
16	0.2492
17	0.3310
18	0.3126
19	0.3063
20	0.3398
21	0.3483
22	0.5087
23	0.4751
24	0.4514
25	0.4053
26	0.4616
27	0.4157
28	0.3930
29	0.4056
30	0.3981
31	0.4983
32	0.4704
33	0.3818
34	0.5544
35	0.4585
36	0.4781
37	0.4565
38	0.5014
39	0.4554
40	0.4449
41	0.5050
42	0.4725
43	0.5526
44	0.5056
45	0.5149
46	0.4661
47	0.4738
48	0.4788
49	0.4991
50	0.4765

IV. CONCLUSIONS AND RECOMMENDATIONS

The lack of significant learning exhibited by the force stick controlled tracking indicate that the nature of the task was such that little conceptual or motor skill learning was involved. Likewise, the lack of fatigue effects on these scores indicate that the performance of the task over this duration was relatively non-demanding. Thus, any changes shown to exist in tracking performance using myoelectric control were assumed to be a function of the control system and not the task, and no corrections needed to be made for fatigue effects. The highly significant decrease in error with the myoelectric control system throughout the duration of the experiment was attributed to subjects' learning the performance characteristics of this system.

Although there was some indication of a reduction in the rate of learning in the latter trials of this experiment, extrapolation beyond this range of data indicating either cessation of learning or continuation of learning would be inappropriate. Such conclusions could only be based on extended experimentation, which is highly recommended for future research.

One difference between the two systems noted subjectively during the experimentation was a relative lack of stability or smoothness in the myoelectric output. Although post integration filtering above 30Hz was employed this was not sufficient to produce an output with stability characteristics identical to the force stick. The equipment being utilized had a limited choice of lower bandpass filter settings, and the next lowest setting, 0.3 Hz, induced a long time constant integration.

factor to the output signal causing a severe lag in response to both the onset and cessation of an input signal. It is strongly felt that low bandpass filtration of the integrated myoelectric signal with an upper frequency limit of five to ten Hertz would produce a control signal virtually as stable as a force stick controller without inducing a significant response lag. Future research into this problem is necessary before a meaningful evaluation of the potential of myoelectric control systems can be achieved.

The demonstration of the feasibility of the use of a myoelectric control system in a precision task, using easily applied surface electrodes, serves as encouragement for future non-clinical application of this technique. The extent of potential utilization of this form of control system seems limited only by the number of possible anatomical placement sites and the degree of imagination employed in its application within the area of man-machine interfacing.

APPENDIX A TOTAL ABSOLUTE ERROR SCORES

	Subject 1		Subject 2	
	Force Stick	Myoelectric	Force Stick	Myoelectric
1	42.16	137.06	52.47	120.54
2	55.31	106.56	50.07	100.17
3	44.49	122.19	42.48	93.15
4	33.43	145.33	46.98	63.43
5	49.52	132.14	50.46	75.98
6	37.81	146.98	41.28	69.05
7	43.96	205.60	40.75	98.66
8	48.26	133.04	47.67	99.57
9	34.98	112.59	39.83	100.79
10	50.71	176.78	43.56	77.37
11	50.03	215.03	47.44	80.62
12	46.13	294.18	38.25	71.04
13	62.77	144.53	45.61	246.92
14	52.96	225.63	47.04	78.18
15	63.05	149.76	36.91	71.90
16	66.42	125.66	38.96	84.21
17	50.38	137.90	36.50	87.93
18	50.61	222.56	42.30	71.24
19	55.73	230.75	37.54	69.58
20	77.15	131.42	40.37	122.78
21	67.35	162.30	47.00	155.01
22	56.36	89.93	38.47	84.89
23	77.33	82.76	34.65	115.52
24	40.36	60.80	38.01	76.44
25	63.46	123.14	33.25	96.62
26	48.89	79.93	37.53	81.39
27	56.52	106.04	33.14	75.93
28	49.48	146.97	39.39	58.75
29	65.63	98.95	35.85	95.30
30	49.72	113.52	45.82	110.62
31	53.99	88.67	30.64	51.95
32	51.92	82.68	35.67	62.29
33	59.04	103.74	30.47	139.45
34	52.02	113.79	38.04	61.50
35	56.13	110.05	50.15	76.45
36	58.57	84.58	43.67	71.15
37	61.46	157.81	29.15	78.62
38	46.48	107.84	48.10	81.08
39	46.75	78.62	39.87	70.24
40	47.07	88.40	31.38	71.68
41	61.34	112.26	62.15	90.44
42	73.45	82.33	41.16	64.06
43	55.74	91.12	42.79	69.94
44	52.60	85.02	44.54	66.35
45	63.27	111.65	43.75	67.71
46	50.55	75.00	45.94	58.34
47	53.93	51.12	48.24	71.15
48	47.24	68.23	41.80	86.65
49	69.04	62.45	37.76	97.23
50	61.57	69.29	40.37	88.99

Total Absolute Error Scores (Cont.)

	Subject 3		Subject 4	
	Force Stick	Myoelectric	Force Stick	Myoelectric
1	43.09	79.53	81.70	199.76
2	61.13	61.61	84.28	244.37
3	47.21	87.88	89.61	158.33
4	50.27	106.80	108.88	178.27
5	43.13	60.59	95.73	185.48
6	49.13	150.46	90.32	279.14
7	42.53	114.50	89.33	303.45
8	39.29	74.03	92.53	304.90
9	48.32	64.31	69.17	274.70
10	47.12	63.19	93.91	201.91
11	42.71	58.82	81.66	345.23
12	39.63	95.93	90.37	372.50
13	45.59	65.56	66.43	259.46
14	39.30	43.89	78.88	230.35
15	52.72	66.08	87.76	326.21
16	47.75	58.77	93.92	320.24
17	41.16	57.64	81.58	233.01
18	39.30	53.19	98.06	223.69
19	37.90	75.60	57.49	194.48
20	41.00	49.73	97.40	154.34
21	43.92	51.03	86.78	215.66
22	47.44	59.81	77.34	116.90
23	38.84	49.37	78.64	180.66
24	49.22	67.69	80.49	146.28
25	35.75	77.87	90.18	235.34
26	46.12	61.74	68.42	186.74
27	47.45	63.45	78.10	194.29
28	54.36	59.41	86.90	241.69
29	34.68	65.62	81.80	153.89
30	39.14	62.96	70.60	165.24
31	40.71	51.54	107.71	193.50
32	50.25	62.27	128.57	178.15
33	45.75	57.55	92.81	171.21
34	44.13	58.68	129.91	194.94
35	46.50	67.86	91.09	167.09
36	41.60	71.48	131.41	211.90
37	44.88	57.15	93.11	171.78
38	39.27	69.07	120.54	146.06
39	38.04	60.90	100.93	234.36
40	36.52	60.29	122.84	243.63
41	64.66	80.13	84.43	201.69
42	53.89	48.95	85.30	278.86
43	43.96	56.89	69.29	151.38
44	49.45	62.30	92.43	131.30
45	39.54	56.05	119.57	121.81
46	47.46	58.39	96.28	188.19
47	52.72	66.80	120.59	229.64
48	31.97	67.78	80.33	127.07
49	38.54	77.24	104.29	134.29
50	46.64	47.23	97.86	272.88

Total Absolute Error Scores (Cont.)

	Subject 5		Subject 6	
	Force Stick	Myoelectric	Force Stick	Myoelectric
1	62.54	186.20	60.79	74.27
2	47.82	233.91	52.84	65.05
3	49.67	287.83	44.58	89.25
4	62.43	266.35	48.07	78.34
5	44.87	285.33	44.33	67.72
6	44.01	180.03	37.71	71.55
7	79.59	256.07	47.71	47.47
8	71.00	200.06	48.55	98.35
9	61.81	388.49	32.14	58.99
10	63.92	539.29	56.64	54.33
11	48.54	203.97	43.36	89.58
12	58.04	200.02	38.93	149.67
13	57.08	247.98	38.79	72.29
14	60.59	221.57	47.29	58.85
15	48.54	431.09	32.87	85.08
16	53.57	517.43	40.73	60.74
17	46.50	225.82	48.04	75.84
18	49.14	205.38	43.52	57.06
19	47.00	169.50	41.36	56.70
20	44.25	198.77	43.76	76.45
21	49.11	280.10	45.06	55.37
22	46.86	190.88	41.22	59.63
23	53.68	201.03	44.01	55.73
24	45.99	284.02	35.23	42.04
25	47.38	179.76	43.91	58.52
26	46.07	160.84	41.04	55.28
27	57.69	193.71	41.31	58.20
28	57.98	151.97	41.11	50.79
29	51.32	226.50	44.68	46.57
30	56.40	203.35	40.08	52.12
31	53.98	223.70	45.15	44.12
32	63.43	284.57	33.43	51.09
33	56.38	370.21	41.09	46.87
34	55.53	117.93	37.24	44.45
35	45.03	265.67	35.76	73.85
36	56.99	193.47	32.10	42.00
37	56.05	178.45	34.38	47.48
38	39.29	205.52	33.58	48.80
39	54.59	195.71	32.16	48.93
40	50.36	246.11	35.31	38.92
41	54.57	123.18	35.68	51.37
42	50.93	129.00	42.07	66.83
43	45.51	119.53	33.54	68.27
44	56.28	245.06	33.19	43.99
45	59.88	208.85	29.12	49.20
46	43.63	253.44	26.43	37.96
47	55.08	153.46	32.54	46.27
48	52.09	179.06	31.49	45.29
49	39.82	139.54	34.10	57.42
50	47.68	142.20	30.11	45.84

Total Absolute Error Scores (Cont.)

	Subject 7		Subject 8	
	Force Stick	Myoelectric	Force Stick	Myoelectric
1	71.47	299.09	72.00	499.11
2	58.80	234.20	53.70	300.18
3	58.60	238.28	63.01	248.46
4	60.23	239.11	64.38	388.78
5	64.45	176.50	50.97	322.89
6	50.70	227.36	62.57	336.72
7	52.16	329.68	57.20	305.69
8	52.09	248.07	60.60	347.21
9	57.21	265.14	47.84	313.13
10	62.33	167.33	48.29	273.28
11	57.08	209.78	53.52	215.45
12	57.74	211.32	39.94	220.42
13	52.60	192.38	64.65	384.68
14	51.52	148.86	49.11	231.72
15	57.74	180.21	41.87	181.81
16	53.40	201.18	54.52	336.16
17	57.89	180.68	45.48	284.38
18	67.29	263.44	40.33	262.26
19	56.37	214.97	55.02	375.00
20	64.67	261.20	38.86	255.39
21	66.83	114.73	44.33	185.35
22	71.70	104.16	44.87	128.73
23	59.44	108.41	35.38	100.52
24	72.68	141.52	48.09	122.24
25	55.35	157.93	27.32	118.73
26	63.03	175.14	30.45	119.19
27	55.84	202.21	32.98	127.95
28	82.10	242.52	38.68	128.62
29	73.38	186.88	44.62	173.60
30	65.70	179.64	35.85	179.44
31	54.93	119.90	35.03	78.91
32	65.33	101.68	32.70	80.33
33	65.28	152.58	26.88	70.94
34	52.30	109.80	28.71	64.97
35	60.21	96.82	27.85	68.69
36	53.41	114.11	31.86	99.79
37	49.52	145.00	30.99	94.17
38	60.90	100.18	28.53	88.63
39	62.67	107.47	35.84	136.38
40	62.23	108.81	27.68	96.89
41	56.31	87.27	28.65	94.81
42	70.13	107.02	26.79	121.93
43	43.46	84.00	26.47	127.52
44	57.92	105.74	30.58	100.33
45	54.54	113.66	26.28	96.05
46	47.18	124.12	32.75	115.86
47	51.01	135.97	31.21	142.08
48	51.80	101.44	32.73	211.67
49	45.95	95.84	29.46	186.97
50	45.46	86.88	33.12	138.03

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ABSTRACT

Basic research was conducted into the ability of a person to perform a precision tracking task using the myoelectric output of the forearm. The tracking task was performed using both a conventional force stick and the electric output from the same muscle groups involved in operating the force stick. Multiple trials with both systems enabled a good comparison to be made between both control modes. The feasibility of myoelectric control using easily applied surface electrodes was demonstrated as was the existance of a significant learning curve associated with the myoelectric control system. Relative effectiveness of the myoelectric control system ranged from 25 percent to 55 percent of that of the force stick and was highly time correlated. Further learning beyond the duration of this experiment was also implied.

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KEY WORDS	LINK A		LINK B		LINK C	
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